

Discovery of the Silver Isotopes

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Thirty-eight silver isotopes have so far been observed; the discovery of these isotopes is discussed. For each isotope a brief summary of the first refereed publication, including the production and identification method, is presented.

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1. INTRODUCTION

In the ninth paper in the series of the discovery of isotopes, the discovery of the silver isotopes is discussed. Previously, the discoveries of cerium [1], arsenic [2], gold [3], tungsten [4], krypton [5], einsteinium [6], iron [7], and vanadium [8] isotopes were discussed. The purpose of this series is to document and summarize the discovery of the isotopes. Guidelines for assigning credit for discovery are (1) clear identification, either through decay-curves and relationships to other known isotopes, particle or γ -ray spectra, or unique mass and Z-identification, and (2) publication of the discovery in a refereed journal. The authors and year of the first publication, the laboratory where the isotopes were produced as well as the production and identification methods are discussed. When appropriate, references to conference proceedings, internal reports, and theses are included. When a discovery included a half-life measurement, the measured value is compared to the currently adapted value taken from the NUBASE evaluation [9] which is based on the ENSDF database [10]. In cases where the reported half-life differed significantly from the adapted half-life (up to approximately a factor of two), we searched the subsequent literature for indications that the measurement was erroneous. If that was not the case we credited the authors with the discovery in spite of the inaccurate half-life.

2. DISCOVERY OF $^{93-130}\text{Ag}$

Thirty-eight silver isotopes from $A = 93 - 130$ have been discovered so far; these include two stable, 15 proton-rich and 21 neutron-rich isotopes. According to the HFB-14 model [11], ^{155}Ag should be the last particle-stable neutron-rich nucleus. The proton dripline has been reached and it is estimated that five additional nuclei beyond the proton dripline could live long enough to be observed [12]. Thus, about 30 isotopes have yet to be discovered and approximately 55% of all possible silver isotopes have been produced and identified so far.

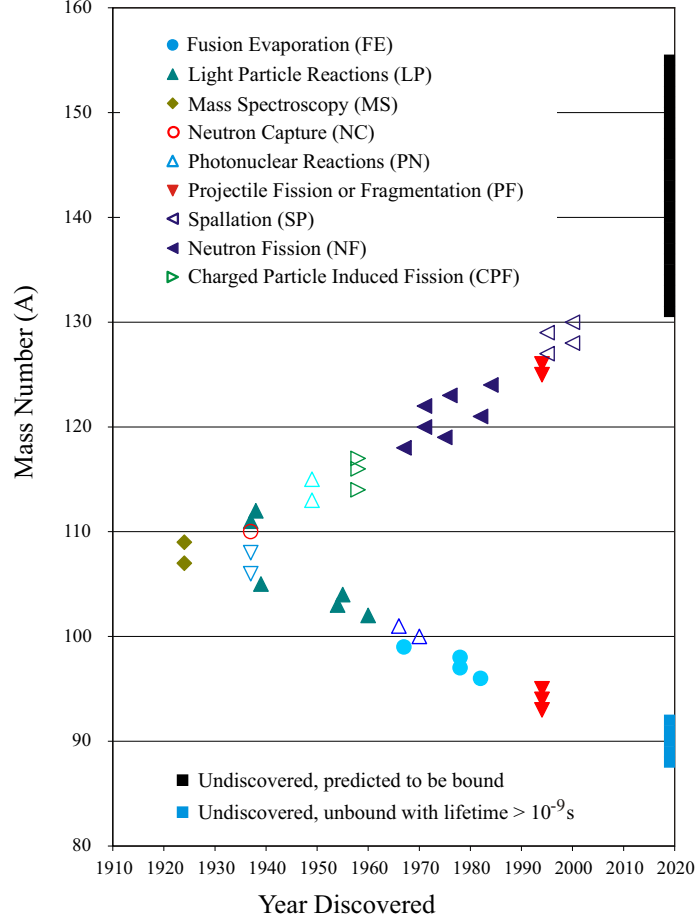


FIG. A. Silver isotopes as a function of time when they were discovered. The different production methods are indicated. The solid black squares on the right hand side of the plot are isotopes predicted to be bound by the HFB-14 model. On the proton-rich side, the light blue squares correspond to unbound isotopes predicted to have lifetimes larger than $\sim 10^{-9}$ s.

Figure A summarizes the year of first discovery for all silver isotopes identified by the method of discovery. The range of isotopes predicted to exist is indicated on the right side of the figure. The radioactive silver isotopes were produced using heavy-ion fusion evaporation (FE), light-particle reactions (LP), neutron-capture reactions (NC), photonuclear reactions (PN), spallation (SP), neutron induced fission (NF), charged-particle induced fission (CPF), and projectile fragmentation or fission (PF). The stable isotopes were identified using mass spectroscopy (MS). Heavy ions are all nuclei with an atomic mass larger than $A = 4$ [13]. Light particles also include neutrons produced by accelerators. Spallation includes fission induced by high-energy protons. In the following paragraphs, the discovery of each silver isotope is discussed in detail.

^{93–95}Ag

In *Identification of new nuclei near the proton drip line*, Hencheck *et al.* report the discovery of ⁹³Ag, ⁹⁴Ag, and ⁹⁵Ag in 1994 [14]. A ¹⁰⁶Cd beam accelerated to 60 MeV/u at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University bombarded a natural nickel target. The isotopes ⁹³Ag, ⁹⁴Ag, and ⁹⁵Ag were analyzed with the A1900 projectile fragment separator and identified event-by-event with measurements of the magnetic rigidity, time of flight, energy-loss, and total energy. “A number of new nuclides were identified including ⁸⁸Ru, ^{90,91,92,93}Rh, ^{92,93}Pd, and ^{94,95}Ag. A few events corresponding to ⁷⁷Y, ⁷⁹Zr, ⁸¹Nb, ⁸⁵Tc, ⁸⁷Ru, ⁹¹Pd, and ⁹³Ag were also observed.” Less than three months later, Schmidt *et al.* reported the discovery of ⁹⁴Ag and ⁹⁵Ag independently [15].

⁹⁶Ag

⁹⁶Ag was discovered by Kurcewitz *et al.* in 1982 and reported in their paper *Investigations of Very Neutron-Deficient Isotopes Below ¹⁰⁰Sn in ⁴⁰Ca-induced Reactions* [16]. A 4.0 A·MeV ⁴⁰Ca beam accelerated by the heavy-ion accelerator UNILAC at the Gesellschaft für Schwerionenforschung (GSI) in Darmstadt, Germany, bombarded a ⁶⁰Ni target. ⁹⁶Ag was produced in the fusion-evaporation reaction ⁶⁰Ni(⁴⁰Ca,p3n) and identified by its β -delayed proton decay: “The proton activity observed at mass 96 was assigned to ⁹⁶Ag from considerations including predicted mass-excess, formation cross-section and the Q-value based preference for odd-N precursors.” The measured half-life of 5.1(4) s is consistent with the currently accepted value of 4.45(6) s.

^{97,98}Ag

⁹⁷Ag and ⁹⁸Ag were discovered by Huyse *et al.* in 1978 as described in the paper *The Decay of Neutron Deficient ⁹⁷Ag, ⁹⁸Ag and ^{99m}Ag* [17]. A ⁹²Mo target was irradiated with a 110 MeV ¹⁴N beam from the CYCLONE cyclotron at Louvain-la-Neuve, Belgium. ⁹⁷Ag and ⁹⁸Ag were identified with Leuven-Isotope-Separator-On-Line (LISOL) and various Ge(LI) γ - and x-ray detectors. “Therefore we postulate that the 686.2- and 1294.1-keV γ rays originate in the decay of ⁹⁷Ag... The presence of [⁹⁷Pd], though not necessarily fed in the β decay, suggests $J^\pi = 6^+$ or 7^+ for the 44.5-sec ⁹⁸Ag that we observe.” The half-life of ⁹⁷Ag was determined to be 21(3) s which is consistent with the accepted value of 25(3) s. The half-life for ⁹⁸Ag was 44.5(12) s which is close to the accepted value of 47.5(3) s. An earlier reported half-life for ⁹⁷Ag of 3 m could not be confirmed [18].

⁹⁹Ag

Decay of the isomeric states of ¹⁰²Ag reported the discovery of ⁹⁹Ag by Bakhru *et al.* in 1967 [19]. Beams of ¹¹B from the Yale Heavy Ion Accelerator were incident on natural molybdenum targets and ⁹⁹Ag was produced in a fusion-evaporation reaction. The resulting activities were measured with Li-Ge detectors and scintillation counters. “During these experiments a positive identification of 10 ± 1 min ¹⁰¹Ag, 8 ± 1 min ¹⁰⁰Ag and 3 ± 0.5 min ⁹⁹Ag activities has been made.” The half-life of 3.0(5) m for ⁹⁹Ag is in reasonable agreement with the currently accepted value of 124(3) s for an isomeric state. Four months later, an independent measurement reported a half-life of 106(10) s [20], however, based on the γ -ray energies measured coincidences it was later speculated that this measurement corresponded probably to ¹⁰⁰Ag [21].

¹⁰⁰Ag

Hnatowich *et al.* correctly identified ¹⁰⁰Ag for the first time in 1970 as reported in *The decay of Cadmium isotopes of mass 100, 101, and 102 to isomers in silver* [21]. A high purity molten tin target was irradiated with 600 MeV protons from the CERN 600 MeV Synchro-cyclotron and ¹⁰⁰Cd was produced in the Sn(p,3pxn) spallation reaction. ¹⁰⁰Ag was then observed in the ISOLDE isotope separator facility. “The ¹⁰⁰Cd does not decay appreciably to the previously known 8 min ¹⁰⁰Ag but, instead, to an isomer of half-life 2.3 ± 0.1 min.” This value for the half-life agrees with the presently accepted value of 2.01(9) m. The incorrect half-life of about 8 m had previously been reported by several authors [19,20,22].

¹⁰¹Ag

In the paper *Neutron-Deficient Silver and Cadmium Isotopes*, Butement and Mirza described the observation of ¹⁰¹Ag in 1966 [22]. 340 MeV protons from the University of Liverpool Synchocyclotron bombarded a silver wool target. “The half life of ¹⁰¹Ag was determined by preparing by spallation a pure silver activity 25 min after the end of irradiation and milking off palladium at regular intervals which varied from 7 to 20 min in different experiments.” A half-life of 14 m was determined which is consistent with the currently adapted value of 11.1(3) m and corresponds to an isomer of ¹⁰¹Ag. About four months later, Panontin and Caretto reported a half-life of 11.2(1) m [23]. They were apparently not aware of the data by Butement and Mirza, however they refer to a conference contribution by Charoenkwan *et al.* as the first observation of ¹⁰¹Ag [24].

¹⁰²Ag

In their 1960 paper *Spins and Decay Modes of Certain Neutron-Deficient Silver Isotopes*, Ames *et al.* identify ¹⁰²Ag correctly for the first time [25]. ¹⁰²Ag was produced by bombarding a ¹⁰²Pd target with 18-MeV protons from the Princeton University cyclotron. The activities were measured with a NaI crystal x-ray counter. “The present work appears to provide the first direct evidence for the existence of a 15-min activity in Ag¹⁰².” This half-life (15(2) m) agrees with the presently accepted value of 12.9(3) m. The observation of ¹⁰²Ag had actually been reported more than 21 years earlier. Although the abstract of the paper by Enns indicates a correct half-life measurement “...and three new periods of 16.3 min (+), 73 min. (+) and 45 days (K capture). The latter are assigned tentatively to Ag¹⁰², Ag¹⁰⁴, and Ag¹⁰⁵, respectively,” the paper itself clearly assigns the 73 min half-life incorrectly to ¹⁰²Ag [26]. It is interesting to note that this assignment was reversed in the 1958 Table of Isotopes [27].

¹⁰³Ag

Halder and Wiig reported the discovery of ¹⁰³Ag in their 1954 article *New Neutron-Deficient Isotope of Iron* [28]. Silver was bombarded with high-energy protons from the University of Rochester 130-inch synchrocyclotron. Following chemical separation, the radioactive decay was measured with an x-ray proportional counter. “... in view of the relatively short half-life of Ag¹⁰⁴ and of the energy available in the transition from the ground state of Ag¹⁰² to that of Pd¹⁰², Ag¹⁰² should have a short half-life. This suggested that our observed 1.1-hour Ag activity was due to Ag¹⁰³, a conclusion which was confirmed by extraction of the known 17-day Pd¹⁰³ daughter.” This half-life is consistent with the adapted value of 65.7(7) m. A half-life of 1.1 h had been previously been observed by Bendel *et*

al., however, they assigned the decay to either ^{102}Ag or ^{104}Ag assuming it corresponded to the 73 m half-life of Enns [26].

^{104}Ag

In *The New Isotopes Cd¹⁰⁴ and Ag¹⁰⁴*, Johnson reported the observation of ^{104}Ag in 1955 [29]. Protons were accelerated to 50 MeV by the McGill University 100 MeV synchrocyclotron and bombarded metallic silver. ^{104}Ag was studied following the decay of ^{104}Cd which was produced in the reaction $^{107}\text{Ag}(p,4n)$ with a 180-degree spectrograph, a lens spectrometer and a scintillation spectrometer. “Since conversion lines had already been found of half-life ~ 59 min., and these showed no growth, it was evident that the 27 min. activity was a daughter product of the 59 min. activity (Cd^{104}) and should therefore be assigned to Ag^{104} .” The 27 m half-life is consistent with the adapted value of a 33.5(2) m isomer. Earlier measurements of a half-life of about 70 m which corresponds to the ground state of ^{104}Ag were inconclusive and were not uniquely assigned to ^{104}Ag (See ^{102}Ag) [26,30].

^{105}Ag

The first observation of ^{105}Ag was reported by Enns in 1939 as described in *Radioactivities Produced by Proton Bombardment of Palladium* [26]. Palladium targets were bombarded with fast protons at the University of Rochester. The decay curves were measured for x-rays, γ -rays, and conversion electrons. “Considering the possible products of p-n reactions, Ag^{105} was the unassigned isotope of odd mass number closest to the stable Ag isotopes. Hence the longest of the periods was assigned to it.” This measured half-life of 45 d is consistent with the presently accepted value of 41.29(7) d. The observation of a 7.5 d half-life reported in a conference proceeding [31] had been incorrectly assigned to ^{105}Ag in the 1937 review of Nuclear Physics [32].

^{106}Ag

Bothe and Gentner first identified ^{106}Ag in their 1937 paper *Herstellung neuer Isotope durch Kernphotoeffekt* [33]. ^{106}Ag was produced in the reaction $^{107}\text{Ag}(\gamma,n)$: “Silber zeigte eine neue Halbwertszeit von 24 min. Von den beiden bekannten, durch Neutronenanlagerung entstehenden Halbwertszeiten wurde außerdem die von 2.3 min erhalten, nicht aber die von 22 sec. Hiernach ist folgende Zuordnung anzunehmen: $\text{Ag}^{106} = 24$ min; $\text{Ag}^{108} = 2.3$ min; $\text{Ag}^{110} = 22$ sec.” (Silver showed a new half-life of 24 min. In addition, of the two known half-lives produced by neutron addition, the 2.3 min half-life was observed, however, not the 22 sec half-life. Therefore, the following assignment can be assumed: $\text{Ag}^{106} = 24$ min; $\text{Ag}^{108} = 2.3$ min; $\text{Ag}^{110} = 22$ sec.). The half-life for ^{106}Ag agrees with the currently accepted value of 23.96(4) m. This assignment was confirmed several times in the same year [34,35,36,31].

^{107}Ag

Aston identified the stable isotope ^{107}Ag in 1924 in *The Mass Spectra of Chemical Elements - Part V* [37]. ^{107}Ag was identified using silver chloride and lithium chloride anodes for the mass spectrometer in Cambridge, England. “Silver has two isotopes, whose masslines when measured against that of iodine have integral values 107 and 109.”

¹⁰⁸Ag

Bothe and Gentner first identified ¹⁰⁸Ag in their 1937 paper *Herstellung neuer Isotope durch Kern-photoeffekt* [33]. ¹⁰⁸Ag was produced in the reaction ¹⁰⁹Ag(γ,n): “Silber zeigte eine neue Halbwertszeit von 24 min. Von den beiden bekannten, durch Neutronenanlagerung entstehenden Halbwertszeiten wurde außerdem die von 2.3 min erhalten, nicht aber die von 22 sec. Hiernach ist folgende Zuordnung anzunehmen: Ag¹⁰⁶ = 24 min; Ag¹⁰⁸ = 2.3 min; Ag¹¹⁰ = 22 sec.” (Silver showed a new half-life of 24 min. In addition, of the two known half-lives produced by neutron addition, the 2.3 min half-life was observed, however, not the 22 sec half-life. Therefore, the following assignment can be assumed: Ag¹⁰⁶ = 24 min; Ag¹⁰⁸ = 2.3 min; Ag¹¹⁰ = 22 sec.). The half-life for ¹⁰⁸Ag agrees with the currently accepted value of 2.37(1) m. Half-lives of 2 m [38] and 2.3 m [39] had been previously reported for silver, however, no mass assignment was made. The assignment was also confirmed two more times in the same year [34,31].

¹⁰⁹Ag

Aston identified the stable isotope ¹⁰⁹Ag in 1924 in *The Mass Spectra of Chemical Elements - Part V* [37]. ¹⁰⁹Ag was identified using silver chloride and lithium chloride anodes for the mass spectrometer in Cambridge, England. “Silver has two isotopes, whose masslines when measured against that of iodine have integral values 107 and 109.”

¹¹⁰Ag

Bothe and Gentner first identified ¹¹⁰Ag in their 1937 paper *Herstellung neuer Isotope durch Kern-photoeffekt* [33]. They made the assignment based on the non-observation of ¹¹⁰Ag in photonuclear reactions on ¹⁰⁷Ag and ¹⁰⁹Ag: “Silber zeigte eine neue Halbwertszeit von 24 min. Von den beiden bekannten, durch Neutronenanlagerung entstehenden Halbwertszeiten wurde außerdem die von 2.3 min erhalten, nicht aber die von 22 sec. Hiernach ist folgende Zuordnung anzunehmen: Ag¹⁰⁶ = 24 min; Ag¹⁰⁸ = 2.3 min; Ag¹¹⁰ = 22 sec.” (Silver showed a new half-life of 24 min. In addition, of the two known half-lives produced by neutron addition, the 2.3 min half-life was observed, however, not the 22 sec half-life. Therefore, the following assignment can be assumed: Ag¹⁰⁶ = 24 min; Ag¹⁰⁸ = 2.3 min; Ag¹¹⁰ = 22 sec.). The first measurement of 20 s [38] and 22 s [39] half-lives for silver were made by neutron irradiations, however, no mass assignments were made.

¹¹¹Ag

In *Radioactive Isotopes of Silver and Palladium from Palladium*, Kraus and Cork reported the discovery of ¹¹¹Ag in 1937 [31]. ¹¹¹Ag was produced by bombarding palladium with 6.3 MeV deuterons from the University of Michigan cyclotron. Decay curves were measured with Lauritsen quartz fiber electroscopes and a Wulf string electrometer equipped with an ionization chamber following chemical separation. “If one of the observed periods is due to the isotope of mass 111 then by beta-decay it should produce a radioactive silver since there is no stable silver of mass 111... it appears to be quite certain that this silver activity (180-hr. half-life) must be built up from the 17-min. and not the 13-hr. palladium.” The half-life of 180 h (7.5 d) is consistent with the accepted value of 7.45(1) d.

¹¹²Ag

The radioactive isotope ¹¹²Ag was first produced by Pool in 1938 and reported in the article *Radioactivity in Silver Produced by Fast Neutrons* [40]. Metallic cadmium and indium targets were bombarded with fast neutrons from the Li+H² reaction at the University of Michigan cyclotron. Following chemical separation, the activity was measured with a Wulf string electrometer equipped with an ionization chamber. “Since this period can be obtained only from indium and cadmium, it seems most probable that silver, ¹¹²Ag, is the carrier of the activity and the reaction equations are as follows: $_{49}\text{In}^{115} + _0\text{n}^1 \rightarrow _{47}\text{Ag}^{112} + _2\alpha^4$, and $_{48}\text{Cd}^{112} + _0\text{n}^1 \rightarrow _{47}\text{Ag}^{112} + _1\text{p}^1$.” The observed half-life of 3.2(2) h agrees with the accepted value of 3.130(9) h.

¹¹³Ag

In the 1949 paper *Radioactive Isotopes of Silver Produced by Photo-Disintegration of Cadmium*, Duffield and Knight reported the discovery of ¹¹³Ag [41]. Cadmium oxide enriched with ¹¹⁴Cd was bombarded with 21 MeV betatron x-rays at the University of Illinois. ¹¹³Ag was produced in the (γ,p) reaction and identified following chemical separation. “The silver from the Cd 114 decayed with a half-life of 5.3 hr. over five half-lives, thus establishing that it was Ag 113 made by Cd 114 (γ,p).” The extracted half-life agrees with the presently accepted value of 5.37(5) h. The 1948 Table of Isotopes [42] made the assignment of the 5.3 h half-life based on an unpublished report of the Plutonium Project [43].

¹¹⁴Ag

Alexander *et al.* discovered in 1958 ¹¹⁴Ag as reported in *Short-Lived Isotopes of Pd and Ag of Masses 113-117* [44]. Uranium was bombarded with 15 MeV deuterons at Princeton University and the isotopes were produced in the subsequent fission of uranium. ¹¹⁴Ag was identified following chemical separation by measuring β-particles and γ-rays. ¹¹⁴Ag was identified by a known ¹¹⁴Cd γ-ray: “A level between 0.55 and 0.56 Mev has been found in Cd¹¹⁴ by several investigators using Coulomb excitation of Cd¹¹⁴Cd and neutron capture of Cd¹¹³, and it has been found in the decay by K capture of 50-day In¹¹⁴. The similarity of the energy levels suggest the mass number 114 for the 2.4-min Pd, 5-sec Ag chain.” This half-life agrees with the presently accepted value of 4.6(1) s. The previous observation of a 2 m activity [41] could not be confirmed.

¹¹⁵Ag

In the 1949 paper *Radioactive Isotopes of Silver Produced by Photo-Disintegration of Cadmium*, Duffield and Knight reported the discovery of ¹¹⁵Ag [41]. Cadmium oxide enriched with ¹¹⁶Cd was bombarded with 21 MeV betatron x-rays at the University of Illinois. ¹¹⁵Ag was produced in the (γ,p) reaction and identified following chemical separation: “...the 20-min. silver activity was found to be Ag 115 made by Cd 116 (γ,p).” The extracted half-life agrees with the presently accepted value of 20.0(5) m. A previously observed 20 m activity [45] had been tentatively assigned incorrectly to ¹¹⁴Ag [46].

^{116,117}Ag

Alexander *et al.* discovered in 1958 ¹¹⁶Ag and ¹¹⁷Ag as reported in *Short-Lived Isotopes of Pd and Ag of Masses 113-117* [44]. Uranium was bombarded with 15 MeV deuterons at Princeton University and the isotopes were produced in the subsequent fission of uranium. ¹¹⁶Ag and ¹¹⁷Ag were identified following chemical separation by measuring β -particles and γ -rays. ¹¹⁶Ag was identified by a known ¹¹⁶Cd γ -ray: “Coulomb excitation of Cd¹¹⁶ reveals the presence of a 0.508-Mev level in this nuclide which is, within the experimental error, identical to the γ line of 0.515 Mev observed for the 2.5-min Ag. Because of the similarity of these energy levels, it is proposed to assign the 2.5 min Ag to the mass number 116.” The identification of ¹¹⁷Ag was determined from the relationship to cadmium decay curves: “The Cd decay curves of the successive extracts were analysed into components of chains of masses 115 and 117. The data correspond to a half-period of 1.1 min for Ag¹¹⁷.” These half lives are consistent with the presently accepted values of 2.68(10) m and 73.6(14) s for ¹¹⁶Ag and ¹¹⁷Ag, respectively. The approximately 3 m half-life had been previously observed, however, no definite mass assignment was made [45,46].

¹¹⁸Ag

In the paper *Identification of 5.3-sec ¹¹⁸Ag as a Product of ²³⁸U Fission*, Weiss *et al.* discussed the first observation of ¹¹⁸Ag in 1968 [47]. A uranium solution was irradiated with neutrons in the Vallecitos Nuclear Test Reactor of the U.S. Naval Radiological Defense Laboratory in San Francisco, CA. The chemically separated samples were analyzed using atomic absorption spectrometry. “Analysis by the method of least squares gives a half-life of $5.3^{+0.9}_{-0.7}$ s.” This half-life is close to the accepted value of 3.76(15) s. A previous half-life measurement of 25 s [48] could not be confirmed.

¹¹⁹Ag

¹¹⁹Ag was discovered by Kawase *et al.* in 1975 in their paper *States in ¹¹⁹Cd Studied in the Decay of ¹¹⁹Ag* [49]. ¹¹⁹Ag was observed at the OSIRIS mass separator in fission products from the reactor at Studsvik, Sweden. Conversion electrons, γ -rays, and $\gamma\gamma$ coincidences were recorded. “Only one isomer of ¹¹⁹Ag was found in the present study, and the half-life of this, 2.1 ± 0.1 s, is much shorter than that of its daughters products.” An earlier measurement of a half-life of 17 s [48] could not be confirmed. Also, Aleklett *et al.* submitted their measurement of ¹¹⁹Ag only two months later than Kawase *et al.* [49].

¹²⁰Ag

In 1971 Fogelberg *et al.* reported the first observation of ¹²⁰Ag in *Energy Levels in ^{114,116,118,120,122}Ca as observed in the beta decay of Ag isotopes* [50]. ¹²⁰Ag was produced via thermal neutron fission in a uranium target at the Studsvik R2-0 reactor and separated with the OSIRIS on-line mass-separator facility. Gamma-ray singles and coincidences were measured with Ge(Li) detectors. “The nuclides ¹²⁰Ag and ¹²²Ag have been studied for the first time...” The measured half-life of 1.17(5) s for the ground state agrees with the presently adapted value of 1.23(4) s.

¹²¹Ag

Fogelberg and Hoff discovered ¹²¹Ag in 1982 as reported in *Levels and Transition Probabilities in ¹²¹Cd* [51]. ¹²¹Ag was produced via thermal neutron fission in an uranium target at the Studsvik R2-0 reactor and separated with the OSIRIS on-line mass-separator facility. “Only one β -decaying state of ¹²¹Ag was found. The half-life was determined to 0.72 ± 0.10 s which is almost an order of magnitude shorter than for any of the daughter activities.” This half-life is included in the weighted average to determine the presently accepted value of 0.79(2) s. It should be mentioned that Aleklett *et al.* discussed ¹²¹Ag in a paper submitted four months earlier [52], but since they referred to the half-life measurement of Fogelberg and Hoff as submitted we credit the latter with the discovery.

¹²²Ag

In 1971, Fogelberg *et al.* reported the first observation of ¹²²Ag in *Energy Levels in ^{114,116,118,120,122}Ca as observed in the beta decay of Ag isotopes* [50]. ¹²²Ag was produced via thermal neutron fission in an uranium target at the Studsvik R2-0 reactor and separated with the OSIRIS on-line mass-separator facility. Gamma-ray singles and coincidences were measured with Ge(Li) detectors. “The nuclides ¹²⁰Ag and ¹²²Ag have been studied for the first time...” Although the measured half-life is too large (1.5(5) s) compared the currently accepted value of 520(14) ms, we credit Fogelberg *et al.* with the discovery because the coincident γ -rays of ¹²²Cd were correctly identified.

¹²³Ag

¹²³Ag was discovered by Lund and Rundstam in 1976 as reported in *Delayed-neutron activities produced in fission: Mass range 122-146* [53]. ¹²³Ag was produced via neutron fission in a uranium target at the Studsvik R2-0 reactor and separated with the OSIRIS on-line mass-separator facility. 30 ³He neutron counters were used to measure the delayed neutron activities. “From mass formula predictions the indium and cadmium isobars of this mass are not likely to be delayed neutron precursors. Silver, on the other hand, has a positive neutron window. Consequently, it seems probable that the 0.39 sec activity is due to ¹²³Ag.” The half-life measurement of 390(30) ms is close to the currently accepted value of 296(6) ms.

¹²⁴Ag

¹²⁴Ag was first correctly identified by Hill *et al.* in 1984 as reported in *Identification and decay of ¹²⁴Ag* [54]. ¹²⁴Ag was produced by neutron irradiation of ²³⁵U at the High Flux Beam Reactor at Brookhaven National Laboratory. The isotope was identified in the TRISTAN mass separator facility and γ -ray singles and coincidences were detected with two high-purity germanium detectors. “We attribute the single γ ray at 613.2 keV with a half-life of 0.17 s to come from the decay of ¹²⁴Ag.” The measured half-life of 0.17(3) s agrees with the currently adapted value of 172(5) ms. A previous observation of a half-life of 0.54(8) s for ¹²⁴Ag [55] could not be confirmed.

^{125,126}Ag

Bernas *et al.* discovered ¹²⁵Ag and ¹²⁶Ag in 1994 at GSI, Germany, as reported in *Projectile Fission at Relativistic Velocities: A Novel and Powerful Source of Neutron-Rich Isotopes Well Suited for In-*

Flight Isotopic Separation [56]. The isotopes were produced using projectile fission of ^{238}U at 750 MeV/nucleon on a lead target. “Forward emitted fragments from ^{80}Zn up to ^{155}Ce were analyzed with the Fragment Separator (FRS) and unambiguously identified by their energy-loss and time-of-flight.” The experiment yielded 119 and 19 individual counts of ^{125}Ag and ^{126}Ag , respectively.

^{127}Ag

^{127}Ag was first observed in 1995 by Fedoseyev *et al.* and reported in *Study of short-lived silver isotopes with a laser ion source* [57]. ^{127}Ag was produced by proton-induced fission at the PS-Booster ISOLDE facility at CERN, Switzerland. The identification was achieved by resonance ionization using a chemically selective laser ion source. “Decay properties of the neutron-rich isotopes $^{121-127}\text{Ag}$ were studied with a neutron long-counter and a β -detector.” The half-life was determined to be 109(25) ms which agrees with the currently adapted half-life of 79(3) ms.

^{128}Ag

In 2000 Kautzsch *et al.* reported the discovery of ^{128}Ag in *New states in heavy Cd isotopes and evidence for weakening of the $N = 82$ shell structure*. [58]. A pulsed 1 GeV proton beam from the CERN Proton Synchrotron Booster bombarded a thick $\text{UC}_2\text{-C}$ target and ^{128}Ag was identified using resonance ionization laser ion sources (RILIS) at ISOLDE. The caption of Figure 1 stated “Excerpts of “laser-on” γ -singles spectra for $A = 126$ and $A = 128$... The 95-ms ^{126}Ag and 58-ms ^{128}Ag peaks are only seen in the respective early spectrum.” This half-life corresponds to the presently accepted value of 58(5) ms.

^{129}Ag

^{129}Ag was first observed in 1995 by Fedoseyev *et al.* and reported in *Study of short-lived silver isotopes with a laser ion source* [57]. ^{129}Ag was produced by proton-induced fission at the PS-Booster ISOLDE facility at CERN, Switzerland. The identification was achieved by resonance ionization using a chemically selective laser ion source. “Although the LIS conditions were not optimized, we probably have already “seen” a ^{129}Ag component underlying the ^{129}In isobar; however, with too low intensity to extract a reliable half-life.”

^{130}Ag

In 2000 Kautzsch *et al.* reported the discovery of ^{130}Ag in *New states in heavy Cd isotopes and evidence for weakening of the $N = 82$ shell structure*. [58]. A pulsed 1 GeV proton beam from the CERN Proton Synchrotron Booster bombarded a thick $\text{UC}_2\text{-C}$ target and ^{128}Ag was identified using resonance ionization laser ion sources (RILIS) at ISOLDE. “One of them at an energy of 957 keV, which is only observed in the first time-bin and decays with an estimated half-life of about 50 ms is tentatively attributed to ^{130}Ag decay and may represent the $2^+ \rightarrow 0^+$ transition in neutron-magic $^{130}\text{Cd}_{82}$.” This half-life is currently the only measured value for ^{130}Ag .

3. SUMMARY

The discovery of the isotopes of silver has been cataloged and the methods of their discovery discussed. The assignment of discovery was very difficult for many isotopes. The first half-life measurements for 6 silver isotopes (^{97}Ag , ^{100}Ag , ^{114}Ag , ^{118}Ag , ^{119}Ag , and ^{124}Ag) were incorrect. The half-lives of $^{102-105}\text{Ag}$, and ^{115}Ag were initially assigned to a different isotope. In addition, the half-lives of ^{104}Ag , ^{108}Ag , ^{110}Ag , and ^{116}Ag were first measured without a definite mass assignment.

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EXPLANATION OF TABLE

TABLE I. Discovery of Silver Isotopes

Isotope	Silver isotope
Author	First author of refereed publication
Journal	Journal of publication
Ref.	Reference
Method	Production method used in the discovery: FE: fusion evaporation LP: light-particle reactions (including neutrons) MS: mass spectroscopy PN: photonuclear reactions NC: neutron-capture reactions SP: spallation NF: neutron-induced fission CPF: charged-particle induced fission PF: projectile fragmentation or projectile fission
Laboratory	Laboratory where the experiment was performed
Country	Country of laboratory
Year	Year of discovery

TABLE I. Discovery of Silver isotopes

See page 15 for Explanation of Tables

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Isotope	Author	Journal	Ref.	Method	Laboratory	Country	Year
⁹³ Ag	M. Hencheck	Phys. Rev. C	Hen94	PF	Michigan State	USA	1994
⁹⁴ Ag	M. Hencheck	Phys. Rev. C	Hen94	PF	Michigan State	USA	1994
⁹⁵ Ag	M. Hencheck	Phys. Rev. C	Hen94	PF	Michigan State	USA	1994
⁹⁶ Ag	W. Kurcewicz	Z. Phys. A	Kur82	FE	Darmstadt	Germany	1982
⁹⁷ Ag	M. Huyse	Z. Phys. A	Huy78	FE	Louvain-la-Neuve	Belgium	1978
⁹⁸ Ag	M. Huyse	Z. Phys. A	Huy78	FE	Louvain-la-Neuve	Belgium	1978
⁹⁹ Ag	H. Bakhru	Nucl. Phys. A	Bak67	FE	Yale	USA	1967
¹⁰⁰ Ag	D.J. Hnatowich	J. Inorg. Nucl. Chem.	Hna70	SP	CERN	Switzerland	1970
¹⁰¹ Ag	F.D.S. Butement	J. Inorg. Nucl. Chem.	But66	SP	Liverpool	UK	1966
¹⁰² Ag	O. Ames	Phys. Rev.	Ame60	LP	Princeton	USA	1960
¹⁰³ Ag	B.C. Haldar	Phys. Rev.	Hal54	LP	Rochester	USA	1954
¹⁰⁴ Ag	F.A. Johnson	Can. J. Phys.	Joh55	LP	McGill	Canada	1955
¹⁰⁵ Ag	T. Enns	Phys. Rev.	Enn39	LP	Rochester	USA	1939
¹⁰⁶ Ag	W. Bothe	Naturwiss.	Bot37	PN	Heidelberg	Germany	1937
¹⁰⁷ Ag	F.W. Aston	Phil. Mag.	Ast24	MS	Cambridge	UK	1924
¹⁰⁸ Ag	W. Bothe	Naturwiss.	Bot37	PN	Heidelberg	Germany	1937
¹⁰⁹ Ag	F.W. Aston	Phil. Mag.	Ast24	MS	Cambridge	UK	1924
¹¹⁰ Ag	W. Bothe	Naturwiss.	Bot37	NC	Heidelberg	Germany	1937
¹¹¹ Ag	J.D. Kraus	Phys. Rev.	Kra37	LP	Michigan	USA	1937
¹¹² Ag	M.L. Pool	Phys. Rev.	Poo38	LP	Michigan	USA	1938
¹¹³ Ag	R.B. Duffield	Phys. Rev.	Duf49	PN	Illinois	USA	1949
¹¹⁴ Ag	J. M. Alexander	Phys. Rev.	Ale58	CPF	MIT	USA	1958
¹¹⁵ Ag	R.B. Duffield	Phys. Rev.	Duf49	PN	Illinois	USA	1949
¹¹⁶ Ag	J. M. Alexander	Phys. Rev.	Ale58	CPF	MIT	USA	1958
¹¹⁷ Ag	J. M. Alexander	Phys. Rev.	Ale58	CPF	MIT	USA	1958
¹¹⁸ Ag	H.V. Weiss	Phys. Rev.	Wei68	NF	U.S. Naval Rad. Def. Lab.	USA	1967
¹¹⁹ Ag	Y. Kawase	Nucl. Phys. A	Kaw75	NF	Studsvik	Sweden	1975
¹²⁰ Ag	B. Fogelberg	Phys. Lett. B	Fog71	NF	Studsvik	Sweden	1971
¹²¹ Ag	B. Fogelberg	Nucl. Phys. A	Fog82	NF	Studsvik	Sweden	1982
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¹²³ Ag	E. Lund	Phys. Rev. C	Lun76	NF	Studsvik	Sweden	1976
¹²⁴ Ag	J.C. Hill	Phys. Rev. C	Hil84	NF	Brookhaven	USA	1984
¹²⁵ Ag	M. Bernas	Phys. Lett. B	Ber94	PF	Darmstadt	Germany	1994
¹²⁶ Ag	M. Bernas	Phys. Lett. B	Ber94	PF	Darmstadt	Germany	1994
¹²⁷ Ag	V.N. Fedoseyev	Z. Phys. A	Fed95	SP	CERN	Switzerland	1995
¹²⁸ Ag	T. Kautzsch	Eur. Phys. J. A	Kau00	SP	CERN	Switzerland	2000
¹²⁹ Ag	V.N. Fedoseyev	Z. Phys. A	Fed95	SP	CERN	Switzerland	1995
¹³⁰ Ag	T. Kautzsch	Eur. Phys. J. A	Kau00	SP	CERN	Switzerland	2000

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